DYNAMICS OF BOUNDARY CURRENTS AND MARGINAL SEAS

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LONG TERM GOALS

To describe and understand the dynamics of ocean circulation, with emphasis on western boundary current systems and interactions between the oceans and marginal seas.

OBJECTIVES

Research during the past year has been focused on studies of the exchange between the northwestern Indian Ocean and its bordering marginal seas: the Red Sea and the Arabian (Persian) Gulf. Comprehensive measurements of the exchange through the Bab el Mandeb strait collected in 1994-1995, at the entrance to the Red Sea, have provided the data necessary to study a wide variety of problems including the multi-layer structure of the exchange, its hydraulics, and the dynamics of seasonal and shorter term exchange fluctuations. Similar data collected in the Strait of Hormuz in 1996-1997 have provided the first long-term direct measurements of the exchange between the Persian Gulf and the Arabian Sea. Our objectives in these programs have now turned to the determination of annual mean heat and freshwater fluxes through the straits, to provide constraints on surface flux climatologies for these marginal sea areas, and to modeling of the exchanges to determine the dominant forcing mechanisms that drive the seasonal and short-term exchange fluctuations.

APPROACH

Measurements collected in these programs consist of moored time series observations of currents using profiling (ADCP) and conventional current meters, and of water properties using temperature/salinity chain arrays, complemented by seasonal hydrographic surveys and local meteorological and tide gauge measurements. Modeling of the exchange dynamics includes application of both analytical models for study of atmospherically forced fluctuations in the straits, and numerical models (MICOM) to study the combined buoyancy and wind forced circulations and exchanges within the marginal seas.

WORK COMPLETED

The Bab el Mandeb experiment has resulted in two published journal articles (Murray and Johns, 1997; Pratt *et al*., 1999) and one in press (Pratt *et al*., 1999) that describe the observed exchange structure and its hydraulics. Work is largely complete on two other manuscripts describing the heat and freshwater transports through the Bab el Mandeb strait and the energetic short-term transport fluctuations observed in the strait and their relationship to atmospheric forcing. Analysis of the Strait of Hormuz data is well underway and preliminary calculations of the annual exchange rate through the strait have been made and compared to surface flux climatologies for the Persian Gulf. In addition to the project related research, an ONR-supported workshop was convened at the Stennis Space Center in May 1999 on the "Arabian Marginal Seas and Gulfs", whose final report may be found at *"http://mpo.rsmas.miami.edu/~zantopp/AMSG-report.html"*.

RESULTS

The Bab el Mandeb Experiment

The 18-month measurement program in Bab el Mandeb provided an unprecedented view of the flow structure and exchange fluctuations in the strait. The annual mean outflow of Red Sea water was determined to be 0.37 Sv, with a large seasonal variation ranging from more than 0.6 Sv in winter to nearly zero in late summer. The inflow and outflow transports of the exchange flow were well resolved and showed a repeatable transition between the two-layer winter regime and three-layer summer regime forced by the monsoon wind reversal over the southern Red Sea (Fig. 1). Determination of the

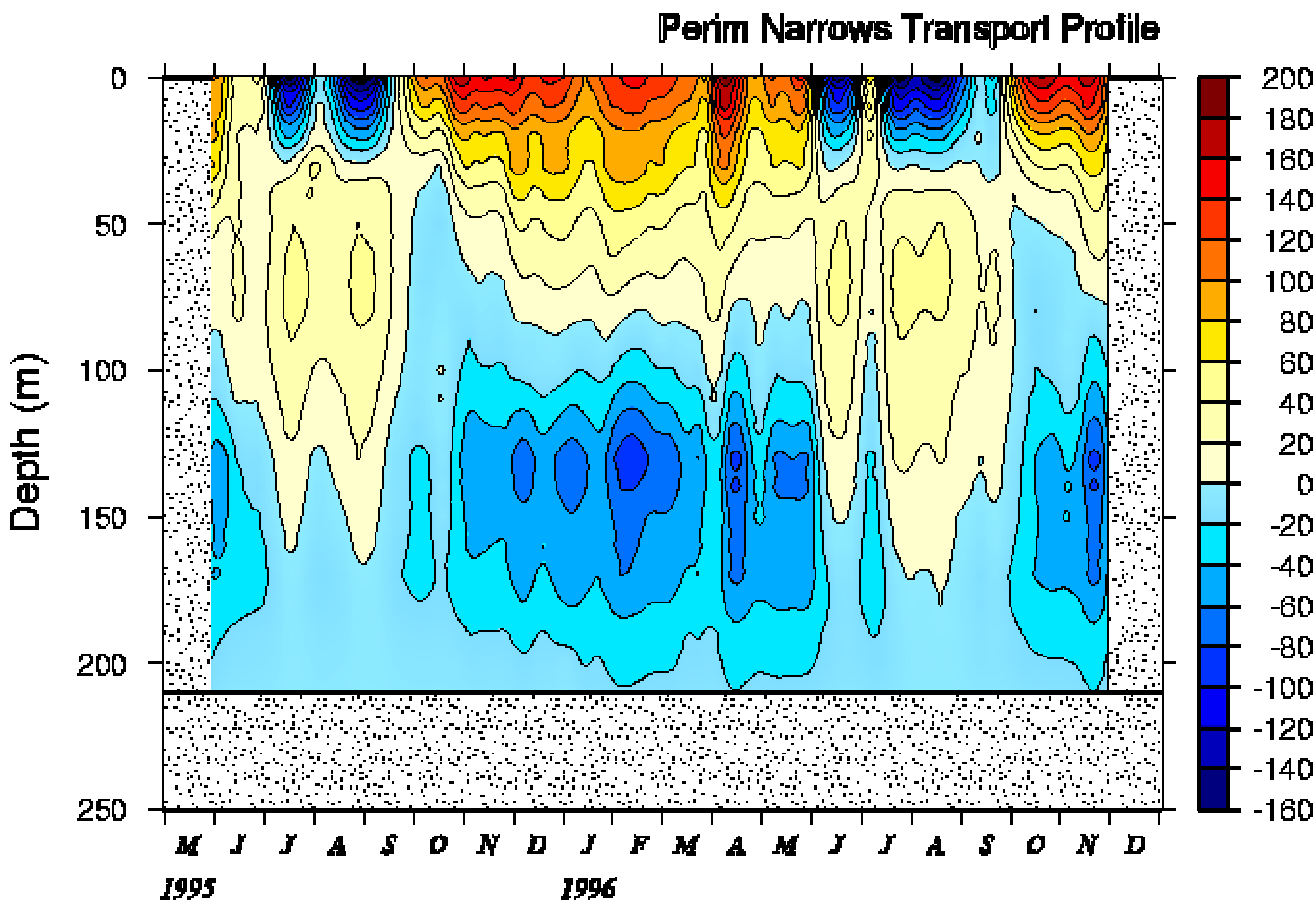


Figure 1. Transport profile from the Perim Narrows section in the Bab el Mandeb strait, for the full 18 month measurement period. Units are 10^2 m^2/s. The transport profile clearly shows the classical two layer exchange flow in winter (October-May) and three layer exchange flow in summer (June-September); red/yellow represent inflow to the Red Sea, blue is outflow.

annual freshwater flux through the strait led to an estimate of 2.1 m/yr for the mean evaporation rate over the Red Sea, slightly larger than available estimates. The heat transport into the Red Sea determined from the measurements has confirmed the existence of a large bias in climatological surface heat flux data (e.g., COADS) over the Red Sea, as recently identified by Tragou *et al*. (1999).

Model simulations using a Red Sea version of the Miami Isopycnal model have produced reasonable agreement with the observed annual cycle (Fig. 2), and have shown that: (i) the seasonal cycle of the exchange is forced in part by surface buoyancy flux variations over the Red Sea and is not driven entirely by winds as previously thought, and (ii) the magnitude of the annual mean exchange with the Indian Ocean is seriously underestimated if only the mean buoyancy forcing in the Red Sea is considered (i.e., a large seasonal cycle of buoyancy forcing over the Red Sea is necessary to accurately model the annual mean exchange rate).

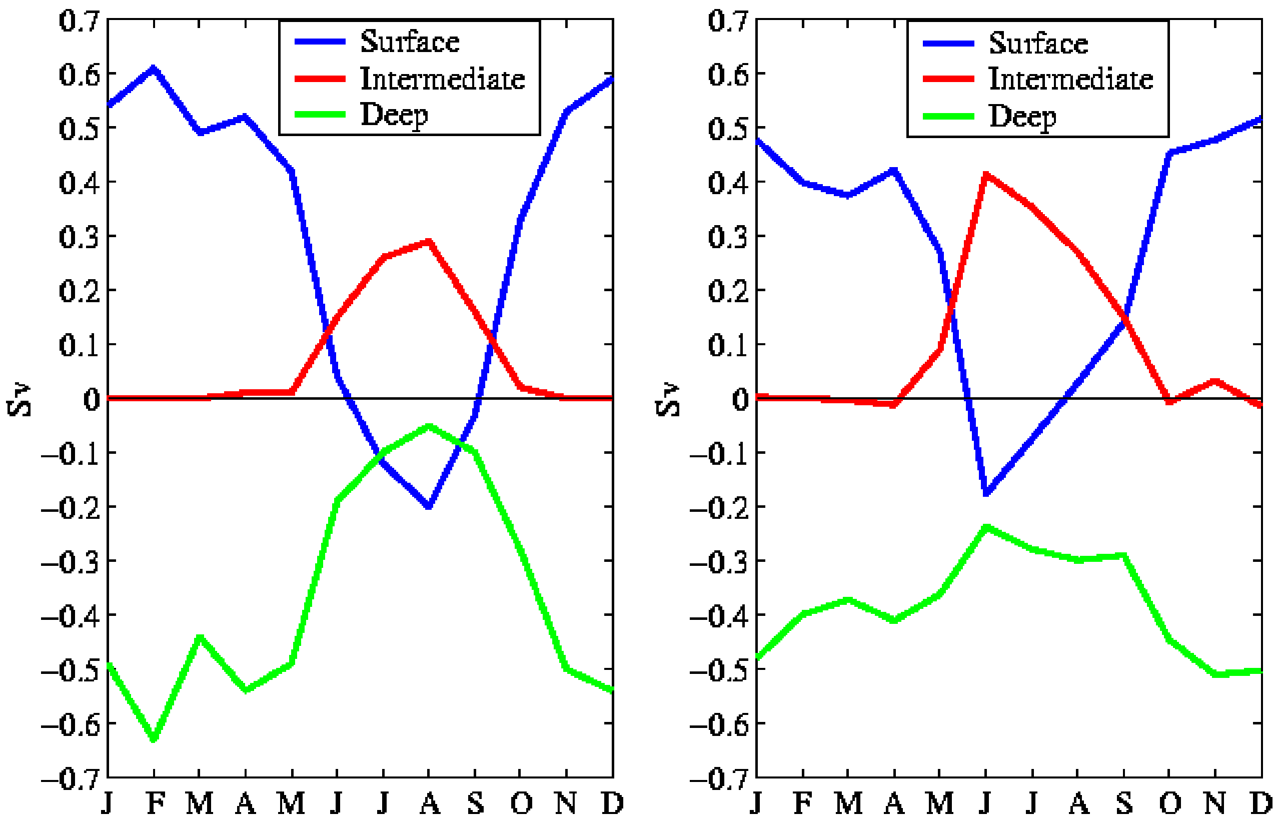


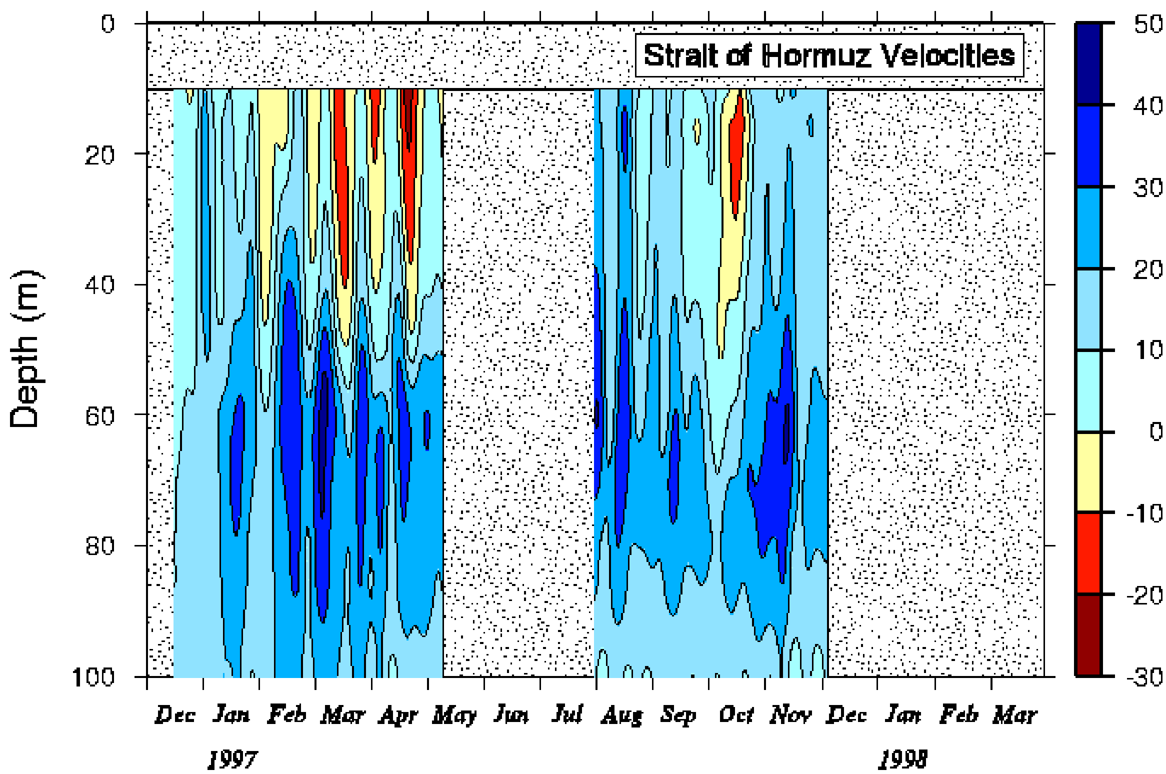
Figure 2. Monthly mean transports through the Bab el Mandeb strait derived from the moored current meter observations (left) and from the MICOM Red Sea model driven by seasonal buoyancy and wind forcing (right). The model captures the basic characteristics of the seasonal exchange cycle, including surface layer reversal in summer, and yields an annual mean exchange rate (0.39 Sv) very close to the observed value of 0.37 Sv.

Synoptic transport variability through the strait on time scales from a few days to weeks is driven by two primary forcing mechanisms: wind stress variability over the strait, and variation in the large-scale barometric pressure over the Red Sea. Transport variations on these time scales can reach amplitudes of up to 0.6 Sv, nearly twice as large as the mean rate of exchange through the strait. Much of this synoptic variability can be explained by a linear, 2-layer frictional model driven by the alongstrait wind stress and a barotropic alongstrait pressure gradient (Johns *et al*., 1998), which shows an enhanced response at the Helmholtz period of the Red Sea of about 5 days.

The Strait of Hormuz Experiment

The time series measurements collected in the Strait of Hormuz in 1996-1997 are the first long term records available there and have revealed new aspects of the flow structure and variability (Fig. 3). The deep outflow from the Persian Gulf does not show a clear annual variation; however, its speed and salinity vary considerably on shorter time scales, with pulse-like events of high salinity outflow (> 40 psu) occurring during winter. The reduced salinity of the deep outflow in late spring suggests a possible decrease in the outflow strength during this season, which unfortunately cannot be confirmed due to a gap in the direct velocity observations.

The surface inflow layer shows significant variation on seasonal as well as shorter time scales. The presence of a weak mean outflow and higher salinity waters in the southern half of the Strait during boreal fall suggests that the cyclonic circulation prevalent in the southeastern Persian Gulf extends partially through the Strait during the fall and winter months. Thus the total exchange through the Strait appears to involve a seasonally active horizontal water exchange with the Gulf of Oman in addition to the more steady thermohaline overturning exchange through the Strait. The magnitude of the annual mean deep outflow of Persian Gulf water through the Strait is estimated to be 0.25 Sv, implying a net evaporation rate over the Gulf of up to 2.4 m/yr. As for the Red Sea, the heat flux through the Strait estimated from these direct measurements implies a significant positive bias in the surface heat flux input to the Persian Gulf in most available flux climatologies.



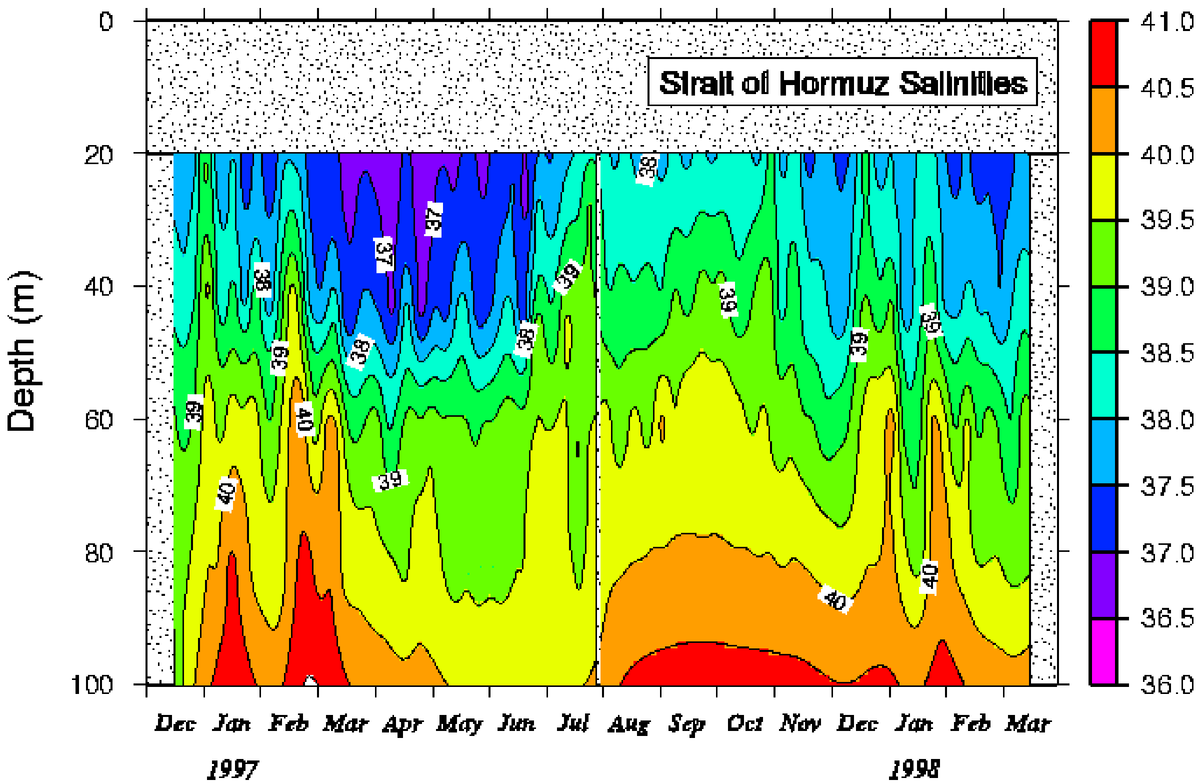


Figure 3. Alongchannel ADCP velocity profile (top), and moored salinity profile (bottom) from the central deep channel in the Strait of Hormuz, after lowpassing the time series data with a 10-day filter. The data were collected in two deployments from December 1996 to July 1997, and August 1997 to March 1998 (ADCP records were short due to battery failures).

IMPACT/APPLICATIONS

These observational programs have provided the first detailed, long-term measurements in these critical straits, and should yield a new level of understanding of the relevant exchange processes and their dynamics. Comparative studies with other marginal sea straits (e.g., Gibraltar) will help to improve and broaden our understanding of the dynamical controls regulating ocean-marginal sea exchange. The heat and freshwater transports determined from these measurements will provide powerful constraints on air-sea fluxes in these regions and help eliminate biases in existing flux climatologies.

TRANSITIONS

The data and results from these projects are being provided to the Naval Research Lab and Naval Oceanographic Office data and modeling groups to provide accurate boundary conditions for their Red Sea and Persian Gulf models and for coupling of these models to the NRL Indian Ocean model.

RELATED PROJECTS

Cooperative work with ONR P.I. Larry Pratt (WHOI) on the hydraulic characteristics of the Bab el Mandeb flow as determined from the project data is continuing. Analysis of the Strait of Hormuz moored time series data is being carried out in collaboration with U.K investigators David Smeed and Simon Josey of the Southampton Oceanography Centre, who performed extensive shipboard surveys in the strait region during the period of the moored deployments, and who are developing and evaluating surface flux climatologies for the region, respectively.

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